On-Line Modeling and New Generation of Supervisory Control System for Sintering Furnaces

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ABSTRACT

LINEMOD is a state-of-the-art universal supervisory control system for monitoring, controlling, and diagnosing sintering furnaces. When applied to a furnace equipped with properly functioning process controls, LINEMOD will improve quality and consistency in heating while substantially lowering gas and fuel consumption. In addition, LINEMOD can help determine furnace operating parameters for new products within the furnace design constraints.

INTRODUCTION

P/M sintering is a complex process for heating pressed parts. It imparts into the parts certain properties that make them usable in automobiles and machines. Since these properties are direct functions of the heating environment existing in a sintering furnace, monitoring and controlling these parameters are important and essential. LINEMOD supervisory control system is capable of monitoring and controlling sintering furnace parameters. A "supervisory" system is one used to augment the physical controls on a furnace by performing functions that are otherwise performed by an operator, e.g., specifying set-points and recording process variables. Some of the furnace parameters that need to be controlled in sintering application are:

- Temperature
- Pressure
- Oxygen and dew-point
- Carbon

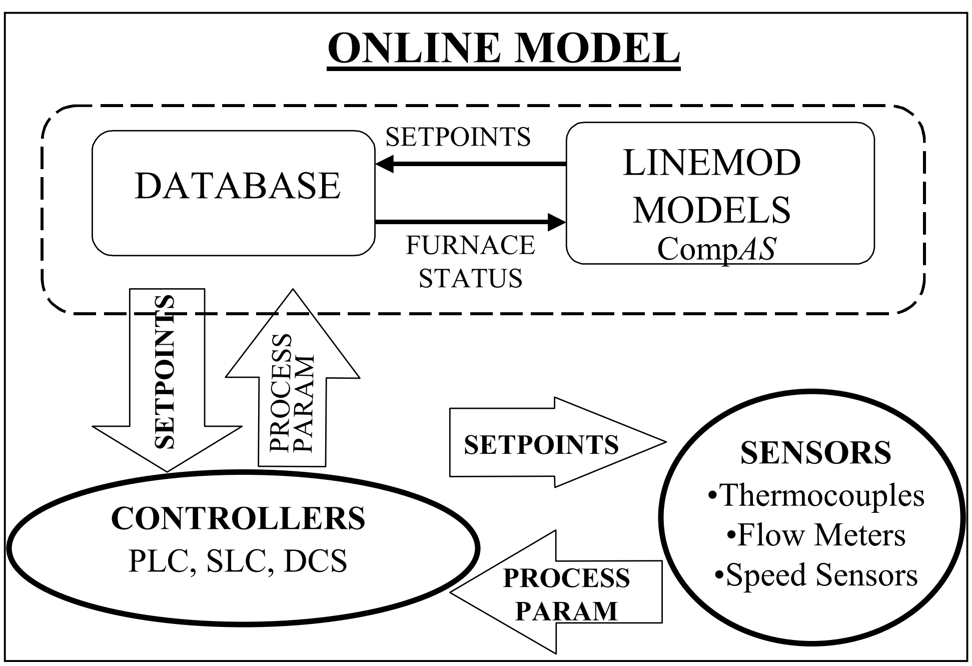
LINEMOD has two models, the off-line model and the on-line model. The Off-line model uses a furnace simulator for furnace inputs while the On-line model monitors an actual furnace. Both models have mathematical models and CAD descriptions of the parts that enable them to calculate the thermal conditions inside the parts being processed. The Off-line model enables the furnace designer or process designer to estimate process variables before the actual furnace and parts are available and to run what-if analyses. The On-line model does real-time tracking of parts being processed in an actual furnace and enables the operator to calculate optimum set-points in real time.

The unique feature of **LINEMOD** is its capability to generate **real-time** set-point parameters using optimization techniques. Moreover, it has the ability to adjust the parameters utilizing statistical process control and adaptive learning.

LINEMOD is a multi-tasking, multi-user software system capable of performing **Human Machine Interfacing (HMI), Charge Scheduling**, **Product Tracking**, **Communication**, **Mathematical Modeling**, **Setpoint Management**, **Adaptive Learning, Data Collection**, and, **Report Generation**. The underlying concepts for the above modules are explained in the following paragraphs.

CONTROL SOFTWARE ELEMENTS

In order for a software system to control and monitor a furnace, it needs to be configured, interfaced to the level I systems (controllers) connected to the sensors, select parts to be heated, run necessary models, and track them as they move through the furnace. The system overview and the data communication path is shown in the following flow diagram.



Following are the major elements (subsystems) of the core software. These elements work together to facilitate the control and provide operational insight into the process.

CHARGE SCHEDULING

In order for the control system to control the furnace parameters, it needs to know certain data for the parts moving through the furnace. These data includes the part dimensions, time at temperature, initial density, material properties of the powder, etc. This data is provided through the Charge Scheduling HMI (Human Machine Interface) which allows the furnace operator to identify to the control system the properties of the parts to be charged and the processing requirements of the parts to be charged. This data may also be received from a separate scheduling computer or the furnace operator's Level-3 computer systems (scheduling or management system). The data is then available for editing through the Charge Scheduling HMI. This element of control is implemented via the Graphical User Interface (GUI).

PRODUCT TRACKING

Furthermore, in order for the control system to control the furnace parameters, it needs to know the location of the parts in the furnace. Thus, the primary function of product tracking is to maintain a map that indicates the physical locations and identification of all the parts inside the furnace.

With the arrival of parts inside the furnace, the information associated with the parts is transferred from the scheduling sub-system to the tracking sub-system. In a continuous furnace with the movement of the belt, tracking will update the position of each part by the amount of distance moved. This information is fed to the math model for updating the part temperature, carbon content, densities, etc.

The furnace tracking system also knows when the part reaches the end of each zone and the discharge position. During part discharge, the furnace tracking system removes the part from the tracking map and the historical records are compiled for the parts for production reporting.

COMMUNICATIONS

To control the furnace parameters and to receive feedback on the operation of the process, the control system needs to communicate with the furnace sensors and controllers. These controllers may be Single Loop Controller (SLC), Programmable Logic Controller (PLC), and Distributed Control Systems (DCS). Based on the feedback, the control parameters are modified to achieve the processing requirements of the parts.

This communication is implemented based on the furnace control devices' communication abilities. Currently, interfaces have been implemented using serial communication protocols and also using Level-1 Control equipment suppliers interface software.

More interfaces will be developed as interface requirements to new Level-1 Control equipment arises.

SIMULATOR

The purpose of the simulator is to provide insight into the process or generate furnace setup parameters without being connected to a furnace. That is, the simulator is a virtual furnace, as designed by operations personnel or engineers, with responses typical of a furnace with full communications capabilities. The simulation includes heating response, cooling response and atmosphere response.
The simulator may be applied for operational or engineering purposes. Applications for this technology may be applied in the following cases:

- Generation of furnace setup parameters for furnaces equipped with controls that do not have communications ability
- testing of multiple furnace designs to achieve processing requirements for specific parts
- "what-if" analysis on new parts or furnace designs

When running the control system off-line, the simulator receives the setpoints from the control system. It then simulates the process, furnace, and response to the setpoints and returns the process feedback to the control system. It is totally transparent to the control system to where the setpoints are going and from where the feedback is being provided and the control system as if a real furnace is attached to the control system.

MATHEMATICAL MODELING

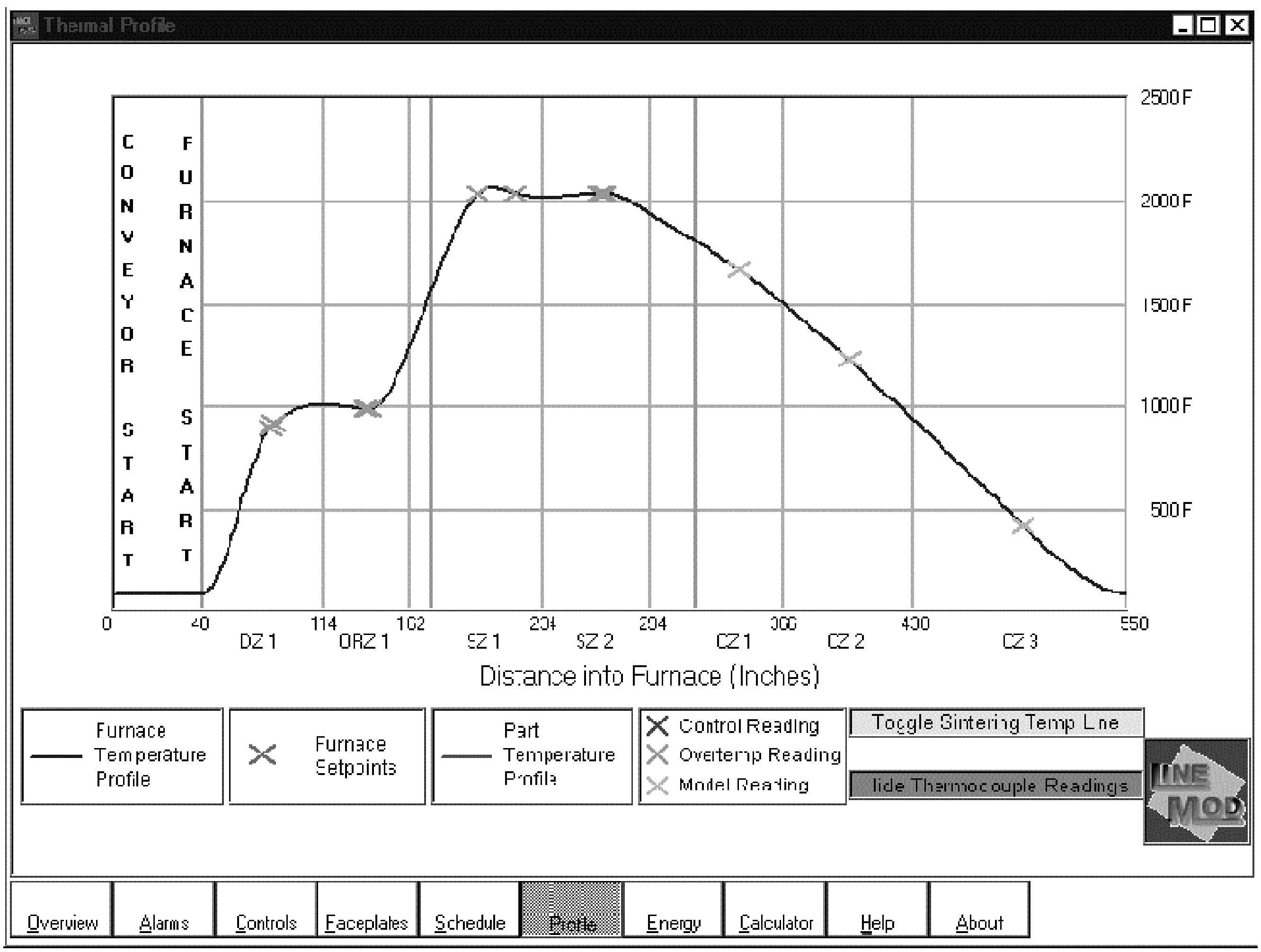
The mathematical model is the primary component of the LINEMOD system. It is required to perform the following tasks:

- Set point generation and management
- Heat Transfer and diffusion calculations
- Energy calculation and heat balance

Math models consist of several techniques and equations that enable the system to predict the transformation taking place inside the part. Some of the techniques that are used in the LINEMOD math models are linear/non-linear interpolation, Linear Programming, Finite Element method, etc.

In order to monitor or predict the changing parameters inside the part, the system has to generate a boundary condition profile inside the furnace and run finite element models to calculate the part parameters.

Profile Generation: The process of generating a continuous boundary condition is termed as profile generation. In this process the system reads the actual data points from the sensors located at various locations along the furnace length. Then these points are fitted with a curve from one end of the furnace to the other. Providing sufficient sensors to measure real data will guarantee an accurate profile. A typical temperature profile is shown below:



Governing Equation: The continuum problems that are solved by the LINEMOD math model for Heat Transfer and Diffusion calculations are usually formulated in terms of governing partial differential equations. For heat transfer, mass diffusion and fluid flow problems, which arise in the analysis of conduction, diffusion, and convection processes; can be represented by a general transport equation as shown below:

$$\gamma \frac{\partial \phi}{\partial \vartheta} + \beta \nabla \bullet (v \phi) - \nabla \bullet (\Gamma \nabla \phi) - \dot{s} = 0$$

where:

ϕ : is the unknown parameter
ϑ : is the time
γ, β, Γ : are known specific properties
v : is the velocity vector
$\dot{s}$: is a volumetric source rate

Boundary Conditions: In addition to the governing differential equations, the appropriate boundary condition must be specified to complete the formulation of the problem. The three types of boundary conditions that are used in the models are:

$\phi = \phi_p$ is the boundary condition of first kind

$-\Gamma \nabla \phi \bullet n = q_p''$ is the boundary condition of second kind, where q_p'' is the normal component of flux

$-\Gamma \nabla \phi \bullet n = h(\phi - \phi_c)$ is the boundary condition of third kind, where ***h*** is the convection coefficient.

Initial Condition: The problem needs to be provided with an appropriate initial condition. The form of the initial condition should be

$\phi = \phi_0$

Data Property: The property data that are used in the above equations are a function of temperature that are pre-determined and stored into a data-base.

Finite Element Method: The numerical scheme used to solve the above differential equation is the Finite Element Method. In this approach, either the variational principles or, preferably the Galerkin method is used to transform the continuum problem to a set of algebraic equations.

SET-POINT DETERMINATION & MANAGEMENT

The unique feature of **LINEMOD** is its capability to generate **real-time** set-point parameters using optimization techniques. Presently we are only determining the zone temperatures, but in the future we will also determine optimum gas flow. The model is capable of generating on-line heating strategy (determination of optimum set-points) during the heating cycle thereby achieving lower fuel and gas consumption and higher throughput. The cooling zone temperature and the fan speed can also be determined in a similar manner.

In conventional practice, the basic control philosophy is to specify the set-point parameters of each heating zone according to a prescribed heating pattern. In our on-line set-point management, this concept is abandoned, and the furnace parameters in zones are directly determined by real time computation using linear programming. When using this method there are a set of constraints and objective function. Examples of such constraints are shown below.

- The mean body temperature of the parts at strategic locations inside the furnace, should be higher than or equal to the estimated or target temperature of the parts at those locations.

- The (Δ T) temperature difference between the coldest and hottest spot should be less than a certain estimated or target value.

- Each control zone operating temperature should be within a prescribed limit.

- Temperature difference between two adjacent zones should be within a prescribed limit.

The above constraints can be represented mathematically. In addition to the above constraints, an objective function can be formulated with the purpose of maximizing the efficiency. Thus the determination of the zone parameters is a linear programming problem where the control variables are the changes in the zone parameters. The solution is obtained easily in real-time.

ADAPTIVE LEARNING

To calculate the "optimal" set-point schedule for which good temperature of the parts are attained, an accurate prediction of zone temperature is required. In addition, it is necessary that the prediction is robust. Robustness refers to the accuracy of the prediction over a wide range of operating conditions. It is not sufficient that predictions be accurate for a repeatable sequence but there must be sufficient accuracy for deviations from this set condition. Robustness allows the calculation of an optimal schedule even though operating conditions may drift significantly. One way to address this competing issue is to adopt a model based adaptive control scheme. In this scheme we attempt to compare the actual measured value with the predicted values from the model. Errors between actual and measured are minimized by appropriately adjusting the parameters of the model.

DATA COLLECTION/REPORT GENERATION

To analyze the operation of a furnace and indeed, operation of a business unit, data on the operation is required. Similarly, data is required for analysis of the parts being manufactured, their quality, and potential processing changes to be made to increase part quality and reduce operational costs.

This element of the control system marshals the production data and the part data from the product tracking subsystem, the mathematical modeling subsystem, and the communications subsystem. It then generates production reports and part reports.

The typical production reports include the following data (as available from the process) on a shift or other user definable time basis:

- Part production rate
- Number of parts produced
- Weight production rate
- Combustion fuel usage
- Atmosphere usage
- Electricity usage
- Utility usage per unit weight of parts
- Etc.

The typical part/charge reports includes the following data (as available from the process) on a part/charge basis:

- Part temperatures and aims at zone boundaries/fixed locations in the furnace
- Part furnace profile temperature at zone boundaries/fixed locations in the furnace
- Density at zone boundaries/fixed locations in the furnace
- Carbon Content at zone boundaries/fixed locations in the furnace
- Part furnace atmosphere profile at zone boundaries/fixed locations in the furnace
- Heating time
- Cooling time
- Etc.

USER INTERFACE

The user interface provides the window into the process. As mentioned in the Charge Scheduling subsystem discussion, the user interface provides the operator the ability to schedule the parts to be processed through the furnace. The user interface also allows the user to configure the part powder properties and part geometry which need to be input into the system:

Further, the user interface also allows the user to view:

- parts tracking through the furnace
- process data received from Level-1 (or the simulator)
- setpoints being generated by the control system
- part data from the math model
- etc.

The user interface is a GUI, graphical user interface. Text is minimized with graphics and plots used to present the data in a more intuitive manner. The HMI screens are point and click navigable with buttons and hot links for navigating the screens.

SCOPE

The scope of the system defines the hardware and software on which the system is implemented. It includes the parts and the interworking of the parts. The scope of the system includes the following:

- The core software in which the control elements discussed above are implemented has been developed with Visual C++.

- The GUI software that communicates to the core software through passed parameters has been developed with Visual Basic.

- The communications to external interfaces reads data from the database and writes the data to the Level-1 controllers. It also reads data from the Level-1 controllers and writes the data to the database. The communications software was developed with Visual C++ and in some cases may include an equipment vendor supplied API (Application Programmers Interface).

- In lieu of communication ability with the Level-1 controls, or indeed, in lieu of an actual furnace, the simulator reads data from and writes data to the database. The simulator was developed with Visual C++.

- The database stores the data that is being passed between the core software and the communications/simulator. The database is implemented using Microsoft Access.

CONCLUSION

P/M sintering process is dependent on time, temperature, atmospheric gas composition, and flow rate. The parts undergoing the sintering process encounter different temperatures and gas composition at different area of the furnace. Moreover, they need to move at a certain speed. Monitoring and controlling each of these parameters precisely results in good quality of parts. In addition, moving the parts at the right speed gives optimum production rate. Keeping track of all of these variables by an operator requires many years of experience. Therefore furnaces should be operated by either experienced operators or by intelligent computer systems. Historically, the art of heating or melting of any product has been acquired through trial and error and subsequently resulted in non-uniform quality, high material rejection, and high fuel consumption. LINEMOD supervisory control software has been developed to address these issues in Industrial Furnace Controls.

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